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Fuel Consumption of Wheeled Vehicle and Transportation Costs during Highway Construction/Reconstruction

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Abstract. A method is proposed for determining the fuel consumption of a wheeled vehicle depending on its speed, road surface flatness and road slope in the longitudinal direction. The purpose of the research is to derive mathematical relationships for calculating the fuel consumption of vehicles, which is one of the transport cost factors during the construction/reconstruction or overhaul of a highway. The proposed polynomial dependencies for calculating fuel in addition to vehicle speed, road surface flatness and its longitudinal slope take into account the mass-dimensional parameters of vehicles involved in road traffic. New mathematical relationships between the speed of wheeled vehicles, road surface flatness and longitudinal road slope allow to simulate the change in the value of fuel consumption of a wheeled vehicle when the speed of traffic flow or the slope of the road surface changes in the forward or reverse direction of the vehicle. In a graphic way, the influence of the pavement slope on the value of fuel consumption, both loaded and unloaded wheeled vehicle is presented. When determining transport costs associated with the highway construction, reconstruction or overhaul it is proposed to use empirical mathematical relationships, which make it possible to obtain fuel consumption with an accuracy of 5 % and save up to 15 % of budget (private) investments. The analysis of scientific publications of the existing approach determine the transport costs associated with highway construction, reconstruction or overhaul. The presented method for determining the fuel consumption of wheeled vehicles with small and large loading capacity increases the accuracy of determining transportation costs and reduces the level of financial costs for highway construction, reconstruction or overhaul.

Keywords: fuel consumption, road conditions, transportation costs, highway, construction, road reconstruction, traffic flow, longitudinal road profile, travel speed

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Расход топлива колесного транспортного средства и транспортные издержки при строительстве/реконструкции автомобильной дороги

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Реферат. Предлагается способ определения расхода топлива колесного транспортного средства в зависимости от скорости его движения, ровности дорожного покрытия и уклона дороги в продольном направлении. Цель исследований – вывести математические зависимости для расчета расхода топлива транспортных средств, являющегося одним из факторов

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транспортных издержек при строительстве/реконструкции или капитальном ремонте автомобильной дороги. Предложенные полиномиальные зависимости для расчета расхода топлива, кроме скорости движения автомобиля, ровности дорожного покрытия и продольного уклона дороги, учитывают массогабаритные параметры транспортных средств, участвующих в дорожном движении. Новые математические взаимосвязи между скоростью движения колесного транспорта, ровностью дорожного покрытия и продольным уклоном дороги позволяют моделировать изменение величины расхода топлива колесного транспортного средства при изменении скорости движения транспортного потока или уклона дорожного покрытия в прямом или обратном направлении движения автомобиля. В графическом виде представлено влияние уклона дорожного покрытия на величину расхода топлива как груженого, так и снаряженного колесного транспортного средства. При определении транспортных издержек, связанных со строительством, реконструкцией или капитальным ремонтом автомобильной дороги, предлагается использовать эмпирические математические зависимости, позволяющие получить расход топлива с точностью до 5 % и сэкономить до 15 % бюджетных (частных) инвестиций. Выполнен анализ научных публикаций существующего подхода по определению транспортных издержек, связанных со строительством, реконструкцией или капитальным ремонтом автомобильной дороги. Приведенный способ определения расхода топлива колесных транспортных средств малой и большой грузоподъемности повышает точность установления транспортных издержек и снижает уровень финансовых затрат на строительство, реконструкцию, капитальный ремонт автомобильных дорог.

Ключевые слова: расход топлива, дорожные условия, пикеты, транспортные издержки, автомобильная дорога, строительство, реконструкция автомобильной дороги, транспортный поток, продольный профиль дороги, скорость движения

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Introduction

Currently one of the key tasks in highway designing and its further operation activities is to increase the efficiency of capital investments in its construction, reconstruction and overhaul by optimizing the design solutions. Economic methods for calculating the effectiveness of project design options provide for the indicator comparison of outcomes and costs for the compared options. This comes down, as a rule, to the calculation of efficiency keeping in mind the economic, social, environmental and other consequences of a particular engineering decision.

When choosing a rational design decision as to the highway construction, reconstruction or overhaul, road construction engineers estimate transportation costs only by averages, which, of course, reduce the accuracy and reliability of any conclusions drawn by them over the benefits of a particular decision. It is known that in transportation costs the largest share is the fuel consumption of a car, which mostly depends on the road conditions of its travelling, therefore, when searching for a rational option for a design decision as to the highway construction, reconstruction or overhaul, it is necessary to increase the accuracy of calculation methods especially for this indicator.

Aim and task setting – the aim of the research is to improve the accuracy of determining the transportation costs associated with the vehicle fuel consumption during the highway operation, as well as during its overhaul period.

Determination of the fuel consumption with changing road conditions

One of the understudied factors while comparing design options is the analysis of changing road conditions during the road operation. In particular, this includes the consistent patterns of changes in the fuel consumption of all vehicles that make up the estimated traffic flow taking into account the change of the rolling resistance coefficient and the carriageway flatness indicators [1–4]. The fuel consumption required for moving on a given road section depends on the road and vehicle parameters [5, 6]. The road characteristics, such as the vehicle speed, longitudinal slope, rolling resistance coefficient and carriageway flatness characteristics, which determine the driving resistance forces and the power losses to move along this particular road segment, participate in the dependencies of fuel consumption in relation to road conditions [7, 8].

The influence of vehicle parameters on fuel consumption [9, 10] is studied in detail and presented in the form of analytical solutions depending on the vehicle speed [11, 12].

In accordance with the road conditions, a driver sets the speed of a car and the road conditions, as it is known, are determined by the plan, road cross section and indicators of the operational road condition [13], so choosing a model for changing the speed of a vehicle is one of the important tasks in determining transportation costs associated with fuel consumption [14, 15].

The relation of the movement speed of different types of vehicles with the plan and the road cross section, based on the generalization of the road conditions outlined in [6], can be represented as shown in Fig. 1 [4]. And you should pay attention to the fact that when moving on the same section of road in different directions, the speed of the same vehicle has not the same character, and, consequently, the transportation costs associated with fuel consumption on direct and the opposite direction of movement will be different.

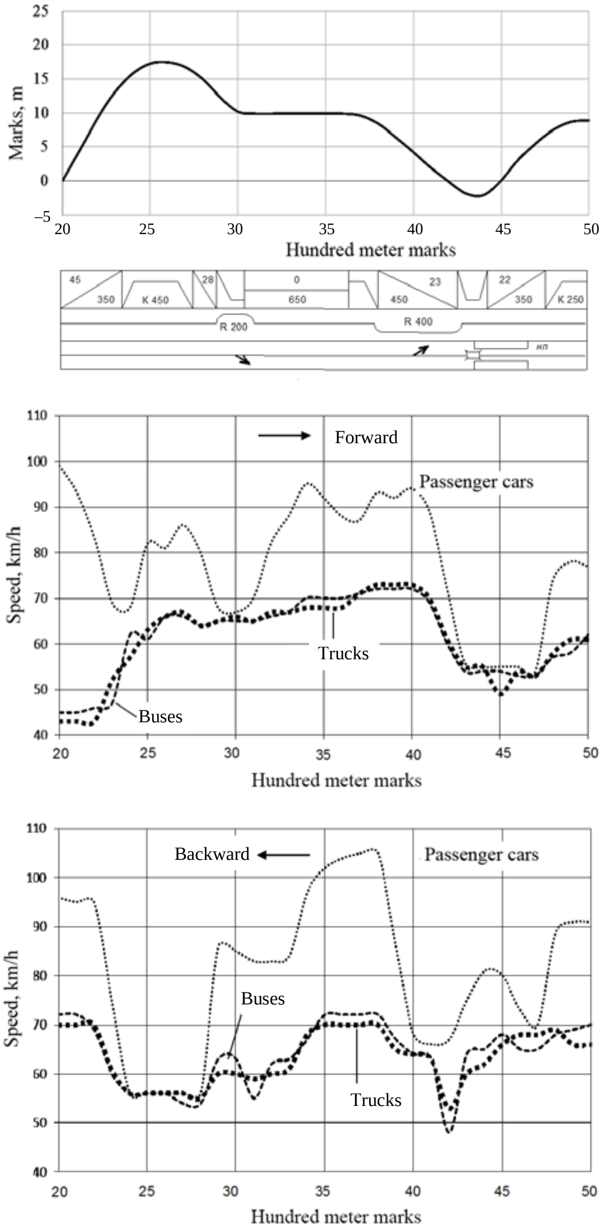

Fig. 1. Relation of vehicle speed with the plan and the longitudinal cross section of a road at an average traffic intensity of 300 cars/h [4]

Solving the problem of determining the fuel consumption of the main types of vehicles with not just changing road conditions on certain road sections but changes in their speed, one must also take into account the influence of the resistance forces and the power losses of the movement in accordance with the studies of the authors' publication [9]. Thus, the offered model for determining transportation costs with fuel consumption during the highway operation, as well as during the overhaul maintenance period, is based on the equation of the fuel consumption [9], obtained by the synthesis of the equations of vehicle motion and partial modes characteristics of internal combustion engine operation

$$G_S = \frac{A}{\eta_i}, \tag{1}$$

where A – parameter combining the fuel consumption with the vehicle speed, road resistance and power capacity per movement [4, 9]; η_i – engine efficiency indicator [9].

Calculating the value of fuel consumption of typical vehicles shows (Fig. 2, 3) [4] that with increasing the slope and increasing vehicle mass, the value of fuel consumption by their internal combustion engines increases. Increasing the speed of a vehicle has a different effect on fuel consumption.

So the calculations showed that increasing the speed to 40 km/h on vehicles of medium and large capacity leads to decreasing the fuel consumption, and their further movement at speeds above 40 km/h leads to increasing the fuel consumption (Fig. 2).

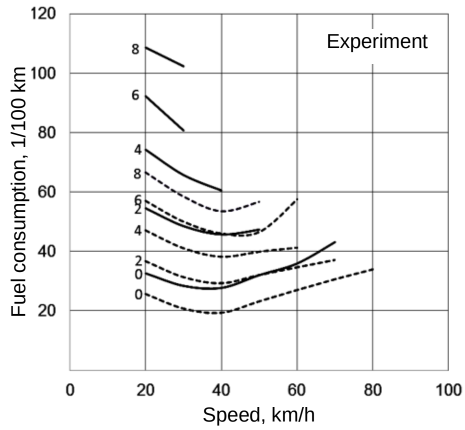

Fig. 2. Fuel consumption of trucks and buses: solid line – loaded car; dotted line – unloaded car (flatness indicator – 50 cm/km; road surface – asphalt concrete; the figures near the curves – road slope, %) [8]

Unlike vehicles with medium and high carrying capacities, vehicles with low carrying capacities have minimal fuel consumption at the speeds of around 60 km/h. Increasing the speed of more than 60 km/h as well as for vehicles with a larger mass, leads to increasing the fuel consumption (Fig. 3).

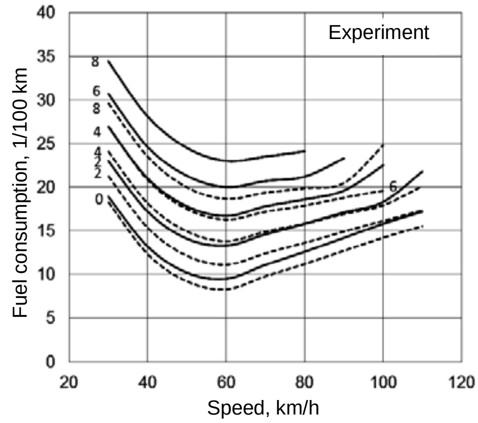

Fig. 3. Fuel consumption of passenger cars: solid line – loaded car; dotted line – unloaded car (flatness indicator – 50 cm/km; road surface – asphalt concrete; figures near the curves – road slope, %) [8]

It should be noted that the equation (1) forming the basis of the offered model for determining transportation costs gives a high accuracy of calculations only for a road that has an excellent carriageway flatness, that is, not more than 50 cm/km. For the roads with a large value of carriageway flatness, the offered method for determining transportation costs combining with the fuel consumption requires the clarification. This is especially relevant in determining transportation costs during the between overhauls period of the road maintenance.

Result and discussion

In order to clarify the effect of the deterioration of the carriageway flatness on the value of fuel consumption, some road experimental studies of the various types of vehicles movement were carried out, the obtained results are shown in Fig. 4, 5.

The carried out studies were performed both for the unloaded condition of a vehicle, and in the conditions of its full loading on the asphalt road. In experimental studies, the average fuel consumption, the vehicle speed and the road flatness were recorded. It should be noted that the speed of passenger cars, trucks with a full carrying capacity up to 3.5 t and buses – up to 5.0 t did not exceed 100 km/h, and the speed of movement of trucks over 3.5 t and buses over 5.0 t did not exceed 70 km/h.

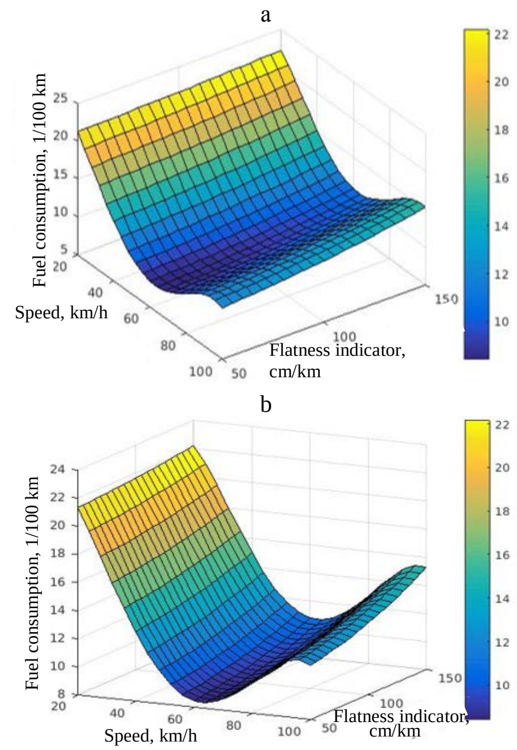

Fig. 4. The dependence of the fuel consumption of passenger cars of the flatness of the road and the speed of the vehicle at its loading state: a – loaded; b – unloaded (road slope – 0 %)

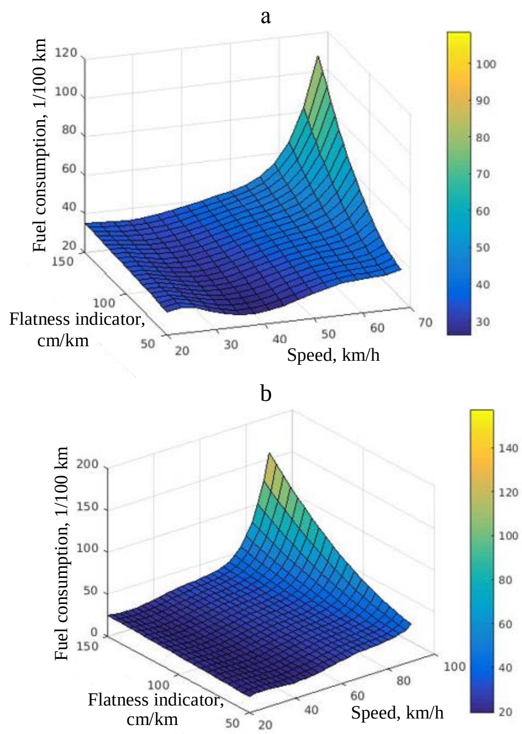

Fig. 5. The dependence of fuel consumption trucks and buses on the flatness of the road and the speed of the vehicle at its loading state: a – loaded; b – unloaded (road slope – 0 %)

The data obtained in the process of experimental studies made it possible to clarify the dependence (1) forming the basis of the model for determining transportation costs by obtaining on its basis new polynomial dependencies:

$$\begin{aligned} Q = {} & 1{,}8i + 23{,}08 - 1{,}32 \cdot 10^{-2} S + 0{,}3652v - \\ & - 3{,}2 \cdot 10^{-5} S^2 + 1{,}057 \cdot 10^{-3} Sv - 0{,}03201v^2 + \\ & + 4{,}539 \cdot 10^{-6} S^2 v - 2{,}564 \cdot 10^{-5} Sv^2 + \\ & + 5{,}027 \cdot 10^{-4} v^3 - 2{,}449 \cdot 10^{-8} S^2 v^2 + \\ & + 1{,}625 \cdot 10^{-7} Sv^3 - 2{,}307 \cdot 10^{-6} v^4; \end{aligned} \quad (2)$$

$$\begin{aligned} Q = {} & 6i - 228{,}2 + 27{,}58v + 2{,}533S - 1{,}115v^2 - \\ & - 0{,}2427vS - 0{,}005529S^2 + 0{,}02066v^3 + \\ & + 0{,}007796v^2 S + 0{,}0004778vS^2 - \\ & - 1{,}773 \cdot 10^{-4} v^4 - 1{,}003 \cdot 10^{-4} Sv^3 - \\ & - 1{,}203 \cdot 10^{-5} v^2 S^2 + 5{,}75 \cdot 10^{-7} v^5 + \\ & + 4{,}398 \cdot 10^{-7} Sv^4 + 9{,}293 \cdot 10^{-8} v^3 S^2; \end{aligned} \quad (3)$$

$$\begin{aligned} Q = {} & 10i - 507{,}1 + 68{,}61v + 4{,}431S - 3{,}237v^2 - \\ & - 0{,}474vS - 1{,}111 \cdot 10^{-2} S^2 + 7{,}089 \cdot 10^{-2} v^3 + \\ & + 0{,}0174v^2 S + 1{,}042 \cdot 10^{-3} vS^2 - \\ & - 7{,}313 \cdot 10^{-4} v^4 - 2{,}577 \cdot 10^{-4} v^3 S - \\ & - 3{,}008 \cdot 10^{-5} v^2 S^2 + 2{,}892 \cdot 10^{-6} v^5 + \\ & + 1{,}305 \cdot 10^{-6} v^4 S + 2{,}707 \cdot 10^{-7} v^3 S^2. \end{aligned} \quad (4)$$

Using the equation (2) it is easy to determine the fuel consumption (l/100 km) of a unloaded or loaded vehicle with low weight (cars, trucks with gross weight up to 3.5 t and buses – up to 5.0 t) given the road flatness (S), its slope (i) and vehicle speed (v).

On the basis of the equation (3), it is possible to calculate the fuel consumption of a unloaded vehicle (a truck over 3.5 t and buses over 5.0 t) using all the same initial parameters (road flatness (S), its slope (i) and vehicle speed (v)).

As the fuel consumption of a loaded vehicle with high carrying capacity (trucks over 3.5 t and buses over 5.0 t) differs significantly from its fuel consumption in the unloaded condition, it is necessary to determine it according to the dependency (4) for more accurate results.

Analyzing the results obtained in the calculation of transportation costs as to the fuel consumption showed that taking into account the change in the fuel consumption of a vehicle at the end of the between-repairs time of the road operation compared to a new road or road after an overhaul has a much higher transportation cost.

For further comparison of design options, it is necessary to take into account the fact that along the road, the traffic flow is uneven in time and space, consisting of different types of vehicles, with different values of fuel consumption, so its share is more than 60 % of the motor transport component of transportation costs.

On any road this component on different road segments may differ significantly from the average value, which makes it possible to find problem road sections by the criterion of transportation costs when searching for the best option.

For such a directional search, it is necessary to solve the problem of differentiating the components of the transportation costs for different road sections, depending on the changing road conditions and the types of vehicles that make up the estimated traffic flow, which significantly increases the reliability of the substantiation of capital investments by the criterion of transportation costs.

If the calculation based on the offered methodology is carried out with reference to the plan and the longitudinal road cross-section (Fig. 1), for example, in the opposite direction, then you can summarize the results and present them in the form of a graph of travel expenditures of fuel by vehicles on different road sections (Fig. 6). On Fig. 6 the following abbreviations are accepted: Fv – freight vehicle up to 3.5 t; Fb – freight vehicle over 3.5 t; Rt – road trains; Bs – buses over 5.0 t; Cs – cars; A – average fuel consumption for the considered flow of vehicles.

It should be noted that since, in accordance with the road map, a vehicle travels over the distances smaller than one kilometre; it is advisable that the fuel consumption dimension l/100 km should be reduced to the fuel consumption dimension l/100 m for the ease analysis of the calculated results. In addition, this dimension with the unit of length measurement (hundred meter mark – 100 m) in a road project is familiar to road engineers.

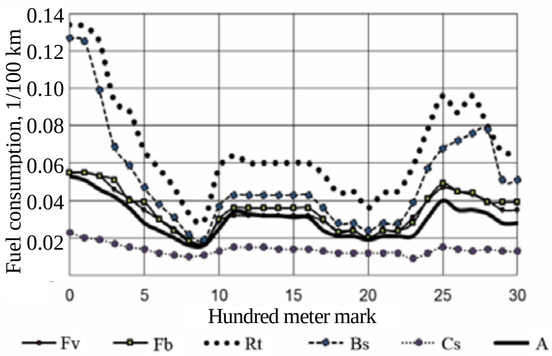

Fig. 6. Fuel consumption depending on the type of a vehicle in the relevant road section

Analyzing the results of calculations in Fig. 6, it is possible to conduct a comparative assessment of the variants of design decisions and choose a rational decision as to the road construction, reconstruction or overhaul.

Analysis of the results of similar calculations performed for other values of slopes and indicators of the rough meter, shows a directly proportional dependence of fuel consumption on the value of the longitudinal slope in the entire speed range of a vehicle. The analysis of the given above modelling results convinces us of the need to take into account an increase of up to 30 % in fuel consumption when driving on an uneven roadway.

CONCLUSIONS

1. Studies conducted on fuel consumption patterns showed that the accuracy of fuel consumption calculations can have an effect of up to 30 % on transport costs compared with averaged calculations.

2. During the overhaul period of the road operation, an accurate calculation of transportation costs saves up to 15 % of the budget funds allocated for the road reconstruction by reducing the amount of consumables in the forward and reverse wheeled vehicle movement.

3. The generalization of traffic flow conditions made it possible to determine with an accuracy of up to 5 % the impact of the speed, the flatness of road surface and the road slope on the value of fuel consumption of typical vehicles to calculate transportation costs determining the level of costs for highway construction, reconstruction and overhaul.

4. Modelling the nature of the change in fuel consumption for different traffic flows shows that when comparing design options, a more accurate calculation of the fuel consumption for all hundred meter marks of the design solution is just as important as the adhesion coefficient and the road evenness indicator.

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